Application to Other Welding Processes

Final Report 278-T-09

For Project

Development of Optimized Welding Solutions for X100 Line Pipe Steel

Prepared for the

Design, Materials, and Construction Technical Committee of
Pipeline Research Council International, Inc.
Project MATH-1 Catalog No. L5XXXX

and

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety
Agreement Number DTPH56-07-T-000005

Prepared by

V.B. Rajan and J. Daniel
The Lincoln Electric Company

September 2011

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3801 Kirby Drive, Suite 520
Houston, Texas 77098
Tel: 713-630-0505
Fax: 713-630-0560
Email: info@ttoolboxes.com

PROJECT PARTICIPANTS

PROJECT TEAM MEMBER	COMPANY AFFILIATION	PROJECT TEAM MEMBER	COMPANY AFFILIATION
Arti Bhatia	Alliance	Jim Costain	GE
Jennifer Klementis	Alliance	Gilmar Batista	Petrobras
Roger Haycraft	Boardwalk	Marcy Saturno de Menezez	Petrobras
David Horsley	BP	Dave Aguiar	PG&E
Mark Hudson	BP	Ken Lorang	PRCI
Ron Shockley	Chevron	Maslat Al-Waranbi	Saudi Aramco
Sam Mishael	Chevron	Paul Lee	SoCalGas
David Wilson	ConocoPhillips	Alan Lambeth	Spectra
Satish Kulkarni	El Paso	Robert Turner	Stupp
Art Meyer	Enbridge	Gilles Richard	TAMSA
Bill Forbes	Enbridge	Noe Mota Solis	TAMSA
Scott Ironside	Enbridge	Philippe Darcis	TAMSA
Sean Keane	Enbridge	Dave Taylor	TransCanada
Laurie Collins	Evraz	Joe Zhou	TransCanada
David de Miranda	Gassco	Jason Skow	TransGas
Adriaan den Herder	Gasunie	Ernesto Cisneros	Tuberia Laguna
Jeff Stetson	GE	Vivek Kashyap	Welpsun
		Chris Brown	Williams

CORE RESEARCH TEAM	
RESEARCHER	**COMPANY AFFILIATION**
Yaoshan Chen	Center for Reliable Energy Systems
Yong-Yi Wang	Center for Reliable Energy Systems
Ming Liu	Center for Reliable Energy Systems
Dave Fink	Lincoln Electric Company
Marie Quintana	Lincoln Electric Company
Vaidyanath Rajan	Lincoln Electric Company
Joe Daniel	Lincoln Electric Company
Radhika Panday	Lincoln Electric Company
James Gianetto	CANMET Materials Technology Laboratory
John Bowker	CANMET Materials Technology Laboratory
Bill Tyson	CANMET Materials Technology Laboratory
Guowu Shen	CANMET Materials Technology Laboratory
Dong Park	CANMET Materials Technology Laboratory
Timothy Weeks	National Institute of Standards and Technology
Mark Richards	National Institute of Standards and Technology
Dave McColskey	National Institute of Standards and Technology
Enrico Lucon	National Institute of Standards and Technology
John Hammond	Consultant Metallurgist & Welding Engineer

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FINAL REPORT STRUCTURE

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277-T-01	Background of Linepipe Specifications	CRES/CANMET
277-T-02	Background of All-Weld Metal Tensile Test Protocol	CANMET/Lincoln
277-T-03	Development of Procedure for Low-Constraint Toughness Testing Using a Single-Specimen Technique	CANMET/CRES
277-T-04	Summary of Publications: Single-Edge Notched Tension SE(T) Tests	CANMET
277-T-05	Small Scale Tensile, Charpy V-Notch, and Fracture Toughness Tests	CANMET/NIST
277-T-06	Small Scale Low Constraint Fracture Toughness Test Results	CANMET/NIST
277-T-07	Small Scale Low Constraint Fracture Toughness Test Discussion and Analysis	CANMET/NIST
277-T-08	Summary of Mechanical Properties	CANMET
277-T-09	Curved Wide Plate Tests	NIST/CRES
277-T-10	Weld Strength Mismatch Requirements	CRES/CANMET
277-T-11	Curved Wide Plate Test Results and Transferability of Test Specimens	CRES/CANMET
277-S-01	Summary Report 277 Weld Design, Testing, and Assessment Procedures for High Strength Pipelines	CRES

Focus Area 2 - Development of Optimized Welding Solutions for X100 Linepipe Steel		
Report #	**Description**	**Lead Authors**
278-T-01	State of The Art Review	Lincoln
278-T-02	Material Selection, Welding and Weld Monitoring	Lincoln/CANMET
278-T-03	Microstructure and Hardness Characterization of Girth Welds	CANMET/Lincoln
278-T-04	Microstructure and Properties of Simulated Weld Metals	CANMET/Lincoln
278-T-05	Microstructure and Properties of Simulated Heat Affected Zones	CANMET/Lincoln
278-T-06	Essential Welding Variables	Lincoln/CANMET
278-T-07	Thermal Model for Welding Simulations	CRES/CANMET
278-T-08	Microstructure Model for Welding Simulations	CRES/CANMET
278-T-09	Application to Other Processes	Lincoln/CANMET
278-S-01	Summary Report 278 Development of Optimized Welding Solutions for X100 Line Pipe Steel	Lincoln

EXECUTIVE SUMMARY

This is the last in the series of topical reports that detail the research leading to the development of the optimized welding solutions for X100 line pipe steel.

In this report, the efficacy of extension of the control methodology for essential welding variables to other processes is examined and discussed. The first application of such an extension is to automatic GMAW with dual torches under field conditions. In addition to the primary essential welding variables (i.e. weld composition preheat and interpass temperature and True Heat Input), torch configuration and the torch spacing were assessed in detail. The statistical model provided linear correlations between mechanical properties and the essential welding variables, including torch configuration and torch spacing. The biggest effect on the response variables (i.e. mechanical properties such as average center line hardness, yield strength and tensile strength) was produced by weld composition, True Heat Input and Preheat / Interpass temperature. The mechanical properties increased dramatically with increasing the weld composition (as measured by P_{cm}) and also with decreasing preheat and interpass temperature and True Heat input. The Charpy toughness increased with decreasing weld composition (Pcm) and increasing preheat/interpass temperature. It was further observed that for a given weld composition, a change in torch configuration from single to dual torch produced a significant decrease in weld metal yield, tensile and hardness properties, a significant increase in weld charpy impact properties, and a significant increase in the HAZ t_{85}. $t_{84,}$ t_{83} cooling times. Decreasing the torch spacing brought further decreases in the weld metal strength and hardness, and increases in weld charpy impact toughness, and decreases in the HAZ t_{85}. $t_{84,}$ t_{83} cooling times. These results highlighted the possibility of modeling the effect of torch configuration along with the other welding variables on weld properties. Transfer functions from these linear correlations enabled the development of a control methodology, which was also applied to actual shop welding to mimic 5G field welding of X100 pipe using dual torch GMAW.

Shop welding experience with two different welding contractors indicated that this control methodology can be implemented effectively in dual torch X100 welding, provided True Heat Input is carefully monitored and controlled around the pipe, and the other variables are controlled within well defined limits. Application of the control methodology for the essential welding variables was found to produce consistent mechanical properties around the pipe.

The essential variable control methodology can be extended to double jointing, which involves joining two smaller lengths of pipe, typically 12 m (40 ft.), in the pipe mill or on a pipe lay barge, by girth welding using SAW or dual torch GMAW to form a longer length of pipe of about 24 m (80 ft.) maximum. In double jointing, because of wider groove geometries and higher heat inputs, the weld metal composition and properties are influenced significantly by the amount of dilution from the base pipe, the extent of which will depend on the welding practice (e.g. number of passes, bead placement, current type and polarity, etc.) and the pipe and consumable compositions. The resulting heat input will be one of the primary variables that determine weld and HAZ properties. True Power or True Energy measurements to get accurate measures of True Heat Input would be essential, especially when using AC/DC machines with varying polarity. Experiments can then be performed to establish statistical models between the essential welding variables and the weld mechanical properties. However, these models would be more complex, because significant interaction between the welding variables such as True Heat Input, preheat and interpass temperature, consumable composition, pipe composition and groove geometry can be expected in their effect on the weld and HAZ mechanical properties. However, with simplification of the problem by holding certain variables such as pipe composition, consumable composition, and groove geometry reasonably constant, the other welding variables such as True Heat Input and preheat and interpass temperatures can be correlated to the weld and HAZ mechanical properties. Such correlations could be developed for controlled cases of X-100 pipe/consumable combinations, which can be the focus of future work. This approach can provide a basis for extending the control methodology to double jointing.

Gas shielded flux cored arc welding (FCAW-G) is commonly used in line pipe construction, particularly with lower strength pipe grades, and has been utilized primarily for tie-in or repair with high strength pipelines. Self shielded flux cored arc welding (FCAW-S) consumables with the ability to satisfy the mechanical properties requirements for X100 pipeline applications are yet to be developed. Both of these FCAW processes employ tubular wires with fill ingredients that produce slag during welding. FCAW-G resembles GMAW except for the fact that the slag-metal reactions can be significant in determining effective heat inputs and cooling rates. FCAW-S does not utilize shielding gas, and its fill ingredients are even more influential in determining the heat input and mechanical properties of the weld. The fill ingredients contain active ingredients that undergo oxidation or react with each other resulting in a very complex heat balance during the welding process, which is also affected by the heat input employed during welding. Consequently, measurements of True Heat Input will not provide the full picture of the total heat input into the process, and modeling the correlation between essential welding variables and mechanical properties is expected to be very complex. Just as in the case with double jointing, simplifying the problem by reducing the number of variables operating simultaneously could make the modeling effort plausible. This could be the focus of future work, particularly with FCAW-G, a process for which consumables close to satisfying mechanical properties requirements are becoming available. If workable models are obtained that correlate weld mechanical properties with a simplified set of welding variables, control methodology for consistent mechanical properties could be developed for FCAW of X100 pipe.

SMAW almost exclusively is used for tie-in and repair with high strength pipelines and for mainline welding with lower strength pipe grades. SMAW is a manual process and the control of heat input is often dependent on the dexterity and skill level of the welder. Current is usually monitored and recorded by visual observations of the current meter on the welding machine, and the travel speed is determined by the welder. While this process does not lend itself easily to control in the conventional sense as obtained with the GMAW process, some measures can be taken to reduce the variation in heat input. If True Power can be recorded in the machine continuously, then efforts can be made to reduce variation in the power input into the weld. If the travel speed can be kept within reasonable control, efforts to minimize heat input variation around the pipe can be implemented. As with the fill material in FCAW wire electrodes, the coating of the SMAW electrodes can have active ingredients that influence the heat input into the weld, and to that extent, True Power monitoring will not capture these effects. But within a constant set of conditions of consumable composition, pipe composition and groove geometry, True Power monitoring could still provide means to implement control methodology to reduce variation in the welding process.

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TECHNICAL REPORT

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V.B. Rajan
Joe Daniel

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In this report, the efficacy of extension of the control methodology for essential welding variables to other processes is examined and discussed. The first application of such an extension is to automatic GMAW with dual torches under field conditions. In addition to the primary essential welding variables (i.e. weld composition preheat and interpass temperature and True Heat Input), torch configuration and the torch spacing are assessed in detail. The statistical model provided linear correlations between mechanical properties and the essential welding variables, including torch configuration and torch spacing. Transfer functions from these linear correlations enabled the development of a control methodology, which was also applied to shop welding to mimic 5G field welding of X100 pipe using dual torch GMAW.

Shop welding experience with two different contractors indicated that this control methodology can be implemented effectively in dual torch X100 welding, provided True Heat Input is carefully monitored and controlled around the pipe, and the other variables are controlled within well defined limits. Successful application of the control methodology for the essential welding variables was found to produce consistent mechanical properties around the pipe. Application of essential variable control methodologies to other processes such as SAW double jointing, FCAW and SMAW are expected to be complex because of interactions, but plausible with problem simplification to minimize the number of variables.

KEYWORDS

GMAW-P, X100 pipe welding, weld metal, HAZ, essential welding variables, True Power, True Heat Input, Average Heat Input, True Energy™

1 INTRODUCTION

The essential variable methodology that was developed for single torch welding can also be extended to dual torch GMAW welding. Dual torch welding has great commercial significance because of the potential it offers for higher productivity and lower construction costs as reported by Hammond [1]. But dual torch welding offers an extra layer of complexity because the thermal effect of the trailing torch has significant influence on the cooling behavior of the leading torch. In addition, the cooling behavior of the bead deposited by the trailing torch is expected to be slower than beads deposited with a single torch. In addition, all of this thermal behavior is significantly affected by the spacing between the torches. For example, in this study it was found that the t_{85} cooling time could be in the order of 2-4 seconds for a single torch at about 0.6 kJ/mm (15 kJ/in) heat input and 100^0C preheat and interpass temperature, whereas the corresponding cooling time for the trail torch in a dual torch configuration with a 51 mm (2 in.) spacing at 0.4 kJ/mm (11 kJ/in) heat input could be in the range of 7-15 seconds. This difference in thermal behavior is expected to produce differences in the amount of softening and resultant mechanical properties of the weld metal and the accompanying heat affected zones. Application of the essential variable methodology to dual torch GMAW welding can help clarify the effect of the dual torch configuration and the welding variables on the weld mechanical behavior.

As reported by Rajan [2], the virtual experiment simulation that was conducted with the integrated thermal-microstructure model indicated a significant effect of torch configuration, in addition to preheat and interpass temperature as well as consumable composition, on weld centerline hardness. The detailed assessment of the dual torch case is presented in this report using the same methodology reported previously [2].

2 TECHNICAL APPROACH

A virtual experiment produced numerical estimates of weld hardness which were used to make a first estimate of welding essential variables and to determine the primary drivers for subsequent experimental work. Further validation was done with a statistical design of experiments (DOE) incorporating experimental plate welds. The DOE was determined using a d-optimal design methodology using Design-Expert® software. In d-optimal design, the DOE points are designed to minimize the variance associated with estimates of the model coefficients of the specified model. In this instance, the DOE matrix was designed to capture all linear effects and two factor interaction effects of the following input variables and responses.

The welding input variables were as follows:

- Preheat/Interpass Temperatures selected were 27^0C, 100^0C, 180^0C
- Consumable composition was varied in the range of Pcm from 0.22 to 0.33 which resulted in variation in weld metal chemistry in the range of Pcm from 0.21 to 0.32
- Groove Offset varied in the range of 2.3-2.8 mm (0.090-0.110 in.).
- True Heat Input was varied in the range of 0.4 kJ/mm (11 kJ/in) to 0.9 kJ/mm (23 kJ/in) by varying the WFS/TS ratio and using two different pulse waveforms such as traditional pulse and a RapidArc® waveform. These provide nominally different values of True Heat Input, for the same wire feed speed/travel speed ratio. For the entire experimental

matrix, the accompanying variation in True Energy/WFS/TS ratio, which is a measure of heat input per unit weld nugget volume, was 0.62-0.89.

- Torch Configuration investigated were Single torch, dual torch with a 100 mm (4 in.) spacing, and dual torch with a 178 mm (7 in.) spacing
- Gas mixture was fixed at 85%Ar/15%CO2

The responses were:

- Hardness traverse through the centerline of the weld
- t_{85} (800-500^{0}C), t_{84} (800-400^{0}C),, t_{83} (800-300^{0}C) HAZ cooling times (measured at 13.4 mm from the bottom of the plate in HAZ near fill pass 2)
- Tensile properties measured with a strip tensile specimen
- Charpy impact toughness over a range of temperatures from 21^{0}C, 0^{0}C, -20^{0}C, -40^{0}C, -60^{0}C, -80^{0}C and -100^{0}C

Statistical methods using analysis of variance were used to determine the significance of the effects of the aforementioned welding input variables on the aforementioned responses. Analysis of variance was used to determine the significance of both linear and interaction effects between the input variables on the aforementioned responses.

3 RESULTS AND DISCUSSION

Results indicate that linear models between the aforementioned input variables and responses could be obtained, and these are discussed in detail in an earlier report [2]. The biggest effect on the response variables (i.e. average center line hardness, yield strength and tensile strength) was produced by weld composition, and then Preheat / Interpass temperature and True Heat Input. Charpy toughness was influenced by weld composition and preheat/interpass temperature. It was further observed that for a given weld composition, a change in torch configuration from single to dual torch produced a significant decrease in weld metal yield, tensile and hardness properties, a significant increase in weld charpy impact properties, and a significant increase in the HAZ t_{85}. $t_{84,}$ t_{83} cooling times. Decreasing the torch spacing from 178 mm (7 in.) to 102 mm (4 in.) brought further decreases in the weld metal strength and hardness, and increases in weld charpy impact toughness, and decreases in the HAZ t_{85}. $t_{84,}$ t_{83} cooling times. These results highlighted the possibility of modeling the effect of torch configuration along with the other welding variables on weld properties. Transfer functions describing the magnitude of the effect of the input variables on the responses were determined and are reproduced in Table 1. These were used to develop recommendations for control of essential variables.

Table 1. Transfer Functions from DOE Plate Welds

Torch Configuration- Single Torch			
Average Center Line Hardness (VHN) =	**166 - 0.23*Preheat/IPT**	**+ 882*Weld Composition (Pcm)**	**- 51*True Heat Input**
Yield Strength (MPa) =	**444 - 0.65*Preheat/IPT**	**+ 2526*Weld Composition (Pcm)**	**- 217*True Heat Input**
Tensile Strength (MPa) =	**332 - 0.63*Preheat/IPT**	**+ 3300*Weld Composition (Pcm)**	**- 148*True Heat Input**
CVN Toughness @-20^{0}C (J) =	**234 + 0.33*Preheat/IPT**	**- 544*Weld Composition (Pcm)**	
HAZ FP2* Cooling Time Ln($t_{85)}$) (s) =	**-0.96 + 0.005*Preheat/IPT**	**+ 2.3*True Heat Input**	
HAZ FP2* Cooling Time Ln($t_{84)}$) (s) =	**-0.39 + 6.95*Preheat/IPT**	**+ 2.3*True Heat Input**	
HAZ FP2* Cooling Time Ln($t_{83)}$) (s) =	**0.34 + 9.66*Preheat/IPT**	**+ 2.2*True Heat Input**	
Torch Configuration- Dual Torch 178 mm (7") Gap			
Average Center Line Hardness (VHN) =	**142 - 0.23*Preheat/IPT**	**+ 882*Weld Composition (Pcm)**	**- 51*True Heat Input**
Yield Strength (MPa) =	**365 - 0.65*Preheat/IPT**	**+ 2526*Weld Composition (Pcm)**	**- 217*True Heat Input**
Tensile Strength (MPa) =	**244 - 0.63*Preheat/IPT**	**+ 3300*Weld Composition (Pcm)**	**- 148*True Heat Input**
CVN Toughness @-20^{0}C (J) =	**266 + 0.33*Preheat/IPT**	**- 544*Weld Composition (Pcm)**	
HAZ FP2* Cooling Time Ln($t_{85)}$) (s) =	**-0.41 + 0.005*Preheat/IPT**	**+ 2.3*True Heat Input**	
HAZ FP2* Cooling Time Ln($t_{84)}$) (s) =	**0.28 + 6.95*Preheat/IPT**	**+ 2.3*True Heat Input**	
HAZ FP2* Cooling Time Ln($t_{83)}$) (s) =	**1.02 + 9.66*Preheat/IPT**	**+ 2.2*True Heat Input**	
Torch Configuration- Dual Torch 100 mm (4") Gap			
Average Center Line Hardness (VHN) =	**135 - 0.23*Preheat/IPT**	**+ 882*Weld Composition (Pcm)**	**- 51*True Heat Input**
Yield Strength (MPa) =	**341 - 0.65*Preheat/IPT**	**+ 2526*Weld Composition (Pcm)**	**- 217*True Heat Input**
Tensile Strength (MPa) =	**211 - 0.63*Preheat/IPT**	**+ 3300*Weld Composition (Pcm)**	**- 148*True Heat Input**
CVN Toughness @-20^{0}C (J) =	**274 + 0.33*Preheat/IPT**	**- 544*Weld Composition (Pcm)**	
HAZ FP2* Cooling Time Ln($t_{85)}$) (s) =	**-0.15 + 0.005*Preheat/IPT**	**+ 2.3*True Heat Input**	
HAZ FP2* Cooling Time Ln($t_{84)}$) (s) =	**0.51 + 6.95*Preheat/IPT**	**+ 2.3*True Heat Input**	
HAZ FP2* Cooling Time Ln($t_{83)}$) (s) =	**1.14 + 9.66*Preheat/IPT**	**+ 2.2*True Heat Input**	

***FP2 = Fill Pass 2**

3.1 Control of Essential Welding Variables in Dual Torch GMAW

The transfer functions listed in Table 1 were used to determine the level of control necessary in the welding process variables to reduce variation in weld mechanical properties. These transfer functions were used to generate optimization graphs for desired yield and tensile strength limits in preheat and interpass temperature vs. True Heat Input space for a given dual torch configuration and weld composition. In this report, optimization graphs using the aforementioned transfer functions for dual torch welding are presented. Two such optimizations are illustrated in Figure 1 and Figure 2 for dual torch welding with spacings of 102 mm (4 in.) and 178 mm (7 in.) respectively.

For weld metal with a nominal composition of 0.25-0.26 Pcm and a preheat/interpass temperature of about 100^{0}C, the envelope of welding variables is defined for a yield strength range of 795-830 MPa (115-120 ksi), tensile strength range of 895-940 MPa (130-136 ksi), and a hardness range of 305-318 VHN. These ranges represent a $\pm$2% variation in each of these properties around their mean value.

For dual torch welds with 102 mm (4 in.) spacing with a nominal weld composition of 0.26 Pcm, the allowable True Heat Input range is between 0.47 mm (12 kJ/in) and 0.63 kJ/mm (16 kJ/in) at 100°C. At 125°C, the allowable True Heat Input range is about 0.4-0.56 kJ/mm (10-14 kJ/in). If the preheat and interpass temperature varies between 100°C and 125°C, then the allowable

True Heat Input range decreases to 0.47-0.56 kJ/mm (12-14 kJ/in). These ranges, are illustrated in Figure 1.

For dual torch welds with 178 mm (7 in.) spacing with a nominal weld metal composition of 0.25 Pcm, the allowable True Heat Input range is between 0.49 kJ/mm (12.5 kJ/in) and 0.65 kJ/mm (16.5 kJ/in) at 100°C. At 125°C, the allowable True Heat Input range is about 0.42-0.57 kJ/mm (10.5-14.5 kJ/in). If the preheat and interpass temperature varies between 100°C and 125°C, then the allowable True Heat Input range decreases to 0.49-0.57 kJ/mm (12.5-14.5 kJ/in). These ranges are illustrated in Figure 2.

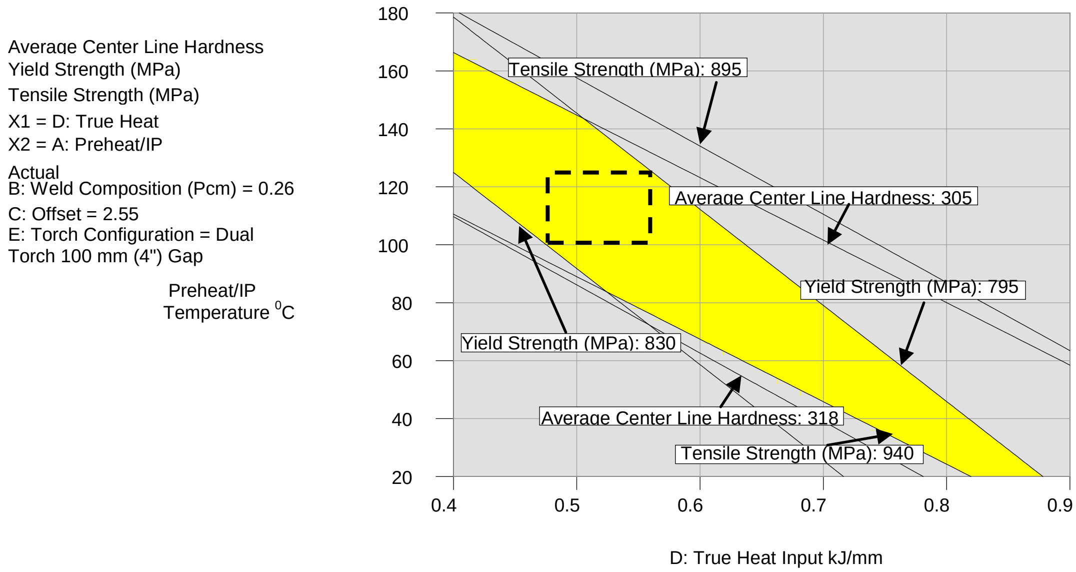


Figure 1. Optimization of yield and tensile strength for a dual torch weld with 102 mm (4 in.) torch spacing and a composition of Pcm 0.26

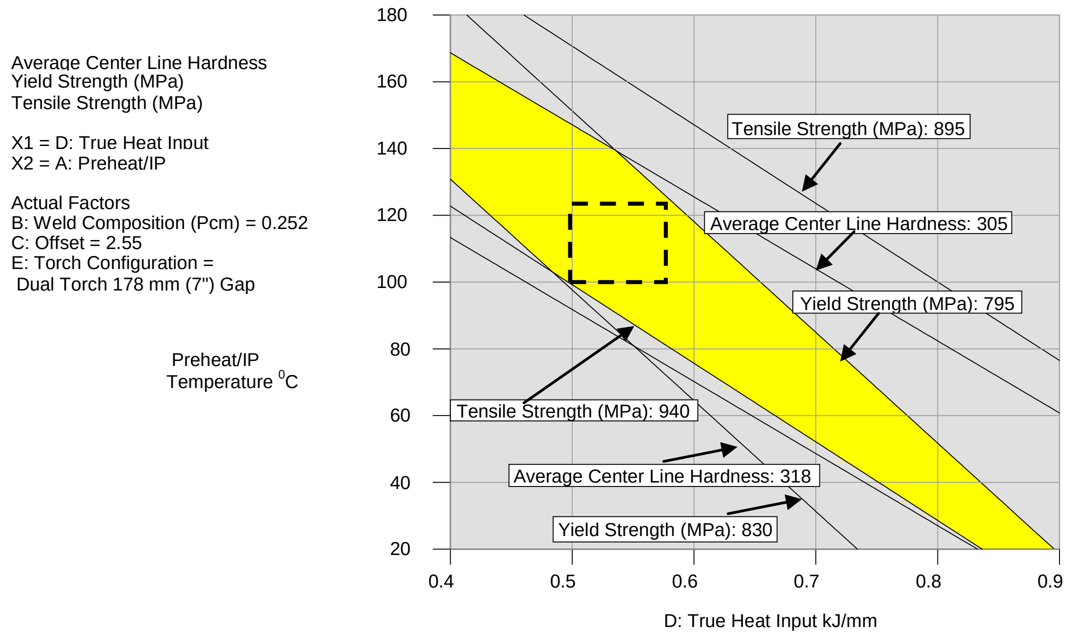


Figure 2. Optimization of yield and tensile strength for a dual torch weld with 178 mm (7 in.) torch spacing and a composition of Pcm 0.25

Keeping the True Heat Input variation within ±0.08 kJ/mm (± 2 kJ/in) for a given preheat and interpass temperature at either torch configuration ensures the mechanical property variation to be within ± 2% of a nominal value. This allows development of the envelope of welding variables for development of the following control methodology.

Using this approach, recommendations for control of the essential variables were outlined for dual torch welding, similar to that outlined for single torch welding [2]. The following recommendations for control are based on the desire to keep the strength variation within ± 2% of a nominal target value. These recommended controls were provided to contractors to fabricate dual welds in their facilities under field welding conditions.

- Preheat and interpass temperatures to be maintained at 100^0C $+15^0$C/-0^0C. Temperature to be measured at 12, 3, 6 and 9 o'clock positions around the pipe to ensure relatively uniform heat distribution.
- Wire Feed Speed (WFS)/Travel Speed (TS) ratio to be maintained as consistent as possible for all fill passes. For the final fill passes, TS could vary as much as 15% or WFS could vary as much as 10% from nominal settings.
- Heat Input (HI) is to be based on True Energy continuously and maintained at ± 0.08 kJ/mm (±2kJ/in) for all fill passes.
- HI/(WFS/TS ratio) tolerance of ± 0.04 for all passes
- Contact tip to work distance to be maintained at ± 3.2 mm (± 0.125 in.) for all passes.
- Groove offset tolerance of ± 0.25 mm (± 0.01 in.).

For purposes of this evaluation, each contractor applied these controls to their own preferred girth weld procedure. In addition, any high/low root fit up condition was located at the 12:00 or 6:00 clock position.

3.2 Contractor Verification of Essential Variable Control in Dual Torch Welding

The methodology for control of essential variables was similar to that implemented in single torch welding [2]. Two contractors A and B were contracted to make two dual torch 5G welds each with two different pipes A and B and weld consumable PT2 with a Pcm of 0.33. Contractor A used dual torches with a spacing of 121 mm (4.75 in.) with pulse waveforms using 85%Ar/15%CO_2 gas. Contractor B used dual torches with a spacing of 51 mm (2 in.) with constant voltage globular transfer using 50%Ar/50%CO_2 gas. Details of the welding procedures are listed in Table 2.

Table 2. Pipe Welding Procedure for Field Welding Conditions

Weld ID	Pipe	Torch Configuration	Torch Gap, mm (in.)	Waveform	Gas	Preheat Temp ^{0}C	Interpass Temp ^{0}C	Consumable	Consumable Pcm
Welds made by Contractor A									
952-G	A	Dual	121 (4.75)	Pulse	85%Ar/15%CO2	100-125	100-125	PT2	0.33
952-H	B	Dual	121 (4.75)	Pulse	85%Ar/15%CO2	100-125	100-125	PT2	0.33
Welds made by Contractor B									
Weld 1	A	Dual	51 (2)	Constant Voltage	50%Ar/50%CO2	100-130	120-180	PT2	0.33
Weld 2	B	Dual	51 (2)	Constant Voltage	50%Ar/50%CO2	100-130	120-195	PT2	0.33

Results of the welding indicated that for dual torch welds 952-G and 952-H, contractor A was able to maintain preheat and interpass temperatures between 100^{0}C and 125^{0}C for all passes. Contractor B on the other hand, started off with preheat in the 110^{0}C-130^{0}C range, and interpass temperatures ranged in the 120^{0}C-180^{0}C for weld 1 and ranged from 120^{0}C-195^{0}C for weld 2 as shown in Table 2.

Measurement of the True Energy for the welds revealed that the difference between True Heat Input and Average Heat Input with contractor A was about 16% in the fill passes, and about 22% in the cap passes, whereas with contractor B the differences were negligible. This is reflective of the fact that contractor A used a pulse waveform and contractor B used a constant voltage process in the globular/shorting mode.

The variation of True Heat Input was analyzed as a function of clock position for each pass as opposed to just looking at the composite True Heat Input for the pass. This was done because data from the 5G welds from the second round of welding indicated that significant variation in heat input could be encountered within a single weld pass. This is because changes are made to the welding procedures at the different clock positions as part of conventional practice to control the weld puddle to provide sound weld metal. Analysis and reporting of the True Heat Input as a function of clock position allows identification of the extent of this variation, such that tighter control can be implemented in field practice.

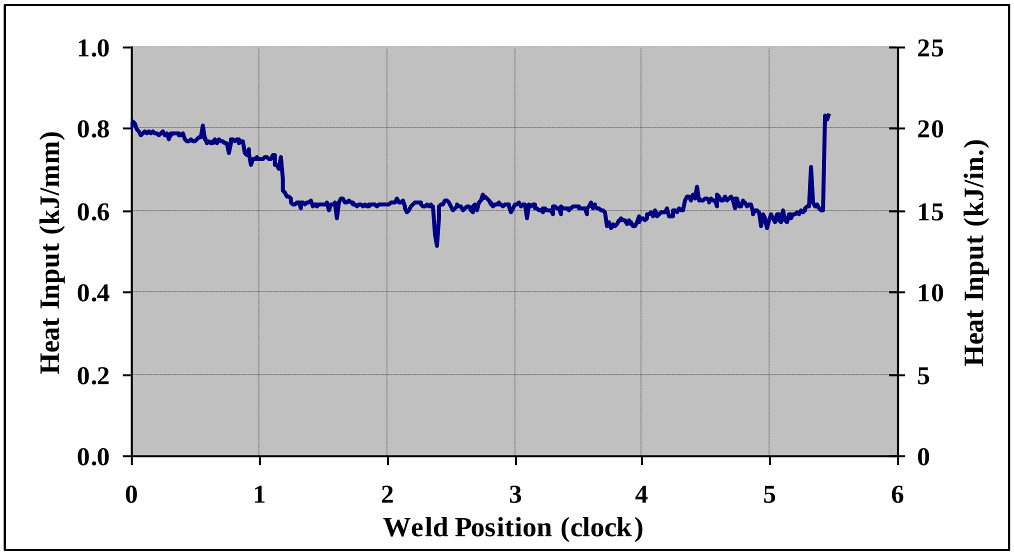


Figure 3. Variation of True Heat Input as a function of clock position, Weld 952-G fill pass 2, Trail Torch, Contractor A

The variation of True Heat Input as a function of clock position with the contractor A revealed that there were several instances where the True Heat Input varied more than ± 0.08 kJ/mm (± 2kJ/in) around the clock position. One example of such variation is shown in Figure 3 where the heat input varied from 0.8 to 0.6 kJ/mm (20 to 15 kJ/in) in going from the 12:00 to 3:00 position and then back to 0.8 kJ/mm (20 kJ/in) near the 5:30 position. The magnitude of this variation was not consistent from pass to pass even though the contractor used his own procedures and methods. Results of the True Heat Input values obtained from welds 952-G and 952-H with contractor A indicating the extent of the variation are shown in Table 3 and Table 4.

Table 3. True Heat Input kJ/mm By Pass, Weld 952-G

							Average Fill Pass 1 to 3	Standard Deviation Fill Pass 1 to 3
Clock Position	Hot Pass	Fill Pass 1 Lead	Fill Pass 2 Trail	Fill Pass 3 Lead	Cap 1 Lead	Cap 2 Trail	FP1-3	FP1-3
12 o'clock	0.31	0.76	0.78	0.65	0.61	0.61	**0.73**	**0.07**
3 o'clock	0.31	0.73	0.61	0.61	0.47	0.48	**0.65**	**0.07**
6 o'clock	0.28	0.79	0.82	0.80	0.59	0.58	**0.80**	**0.01**

Table 4. True Heat Input kJ/mm By Pass, Weld 952-H

							Average Fill Pass 1 to 3	Standard Deviation Fill Pass 1 to 3
Clock Position	Hot Pass	Fill Pass 1 Lead	Fill Pass 2 Trail	Fill Pass 3 Lead	Cap 1 Lead	Cap 2 Trail	FP1-3	FP1-3
12 o'clock	0.31	0.78		0.79		0.61	**0.78**	**0.01**
3 o'clock	0.31	0.78	0.61	0.62		0.48	**0.67**	**0.09**
6 o'clock	0.30	0.84	0.83	0.76		0.63	**0.81**	**0.04**

In weld 952-G, in fill pass 1, the True Heat Input was consistently around 0.73-0.8 kJ/mm (18.5-20 kJ/in). In fill pass 2, the True Heat Input varied as a function of clock position from 0.78 kJ/mm (20 kJ/in) at clock position 12 to 0.6 kJ/mm (15 kJ/in) at clock position 3 and back to 0.82 kJ/mm (21 kJ/in) at clock position 6. In fill pass 3, the true heat input varied from 0.65 kJ/mm (16 kJ/in) at the 12 and 0.61 kJ/mm (15.5 kJ/in) at the 3 clock positions to 0.8 kJ/mm (20 kJ/in) at the 6 clock position. At a given clock position, the heat inputs varied from 0.73 kJ/mm (18.5 kJ/in) in fill pass 1 to 0.61 kJ/mm (15.5 kJ/in) in fill passes 2 and 3 in the 3 clock position, from 0.76-0.78 kJ/mm (19-20 kJ/in) in fill pass 1 and 2 to 0.65 kJ/mm (16 kJ/in) in fill pass 3 in the 12 clock position. In the 6 clock position, the heat input stayed nominally at 0.8-0.82 kJ/mm (20-21 kJ/in) in the fill passes.

In weld 952-H, some data was not recorded because the electrical connections were lost during changeovers. However, the trends of True Heat Input with clock position was similar to that obtained in weld 952-G, except for higher heat input of 0.8 kJ/mm (20 kJ/in) in fill pass 3 in the 12 o'clock position.

With contractor B, most of the variation was in the 12-2 and 4:30-6 clock positions. In between, the True Heat Input variation was in a fairly tight range. A typical example of this is shown in Figure 4. Results of the True Heat input values obtained at the 12, 3 and 6 clock positions from welds 1 and 2 with contractor B are shown in Table 5 and Table 6.

In this instance, in a given fill pass, the variation around the clock position was much smaller. In weld 1, in fill passes 1, 2 and 4, the True Heat Input varied from about 0.5-0.6 kJ/mm (13-15 kJ/in) at the 12 clock position to about 0.45-0.48 kJ/mm (11-12 kJ/in) in the 3 clock position and 0.5-0.56 kJ/mm (13-14 kJ/in) in the 6 o'clock position. In fill pass 3, the heat input was consistently around 0.43-0.47 kJ/mm (11-12 kJ/in) in all positions. In weld 2, in fill passes 1 through 4, the True Heat Input varied from 0.53-0.57 kJ/mm (13.5-14.4 kJ/in) at the 12 clock position to about 0.43-0.47 kJ/mm (11-12 kJ/in) in the 3 clock position and 0.54-0.60 kJ/mm (13.7-15.2 kJ/in) in the 6 clock position. In general, the heat input variation in a pass and from pass to pass was much lower than with contractor A.

Small scale tests were conducted in the clock positions 12-1, 2:30-3:30, and 5-6. These are referred to nominally as 12, 3 and 6 clock positions. Small scale tests reported here include strip tensile tests [4], hardness and Charpy impact toughness tests.

Table 5. True Heat Input (kJ/mm) By Pass, Weld 1

									Average Fill Pass 1 to 4	Standard Deviation Fill Pass 1 to 4
Clock Position	Root	Hot Pass	Fill Pass 1	Fill Pass 2	Fill Pass 3	Fill Pass 4	Cap 1	Cap 2	FP1-4	FP1-4
12 o'clock	0.34	0.35	0.54	0.59	0.47	0.52	0.40	0.43	**0.53**	**0.05**
3 o'clock	0.29	0.31	0.45	0.48	0.43	0.45	0.38	0.40	**0.45**	**0.02**
6 o'clock	0.37	0.39	0.52	0.56	0.45	0.50	0.53	0.55	**0.51**	**0.04**

Table 6. True Heat Input (kJ/mm) By Pass, Weld 2

Clock Position	Root	Hot Pass	Fill Pass 1	Fill Pass 2	Fill Pass 3	Fill Pass 4	Cap 1	Cap 2	Average Fill Pass 1 to 4 FP1-4	Standard Deviation Fill Pass 1 to 4 FP1-4
12 o'clock	0.35	0.32	0.57	0.54	0.53	0.53	0.46	0.43	**0.54**	**0.02**
3 o'clock	0.29	0.28	0.47	0.45	0.43	0.44	0.42	0.41	**0.45**	**0.02**
6 o'clock	0.36	0.34	0.60	0.56	0.54	0.54	0.62	0.59	**0.56**	**0.03**

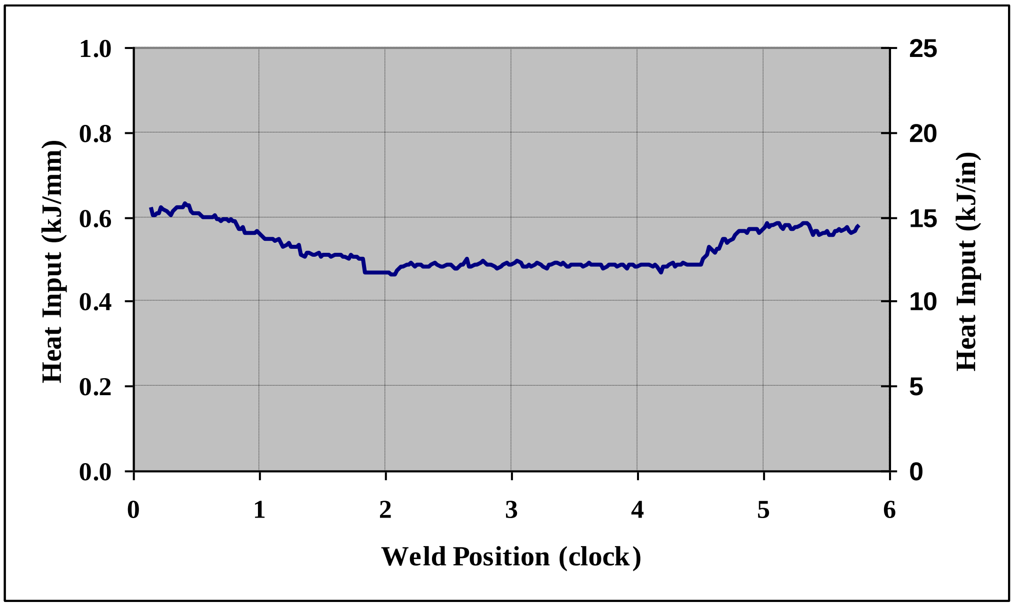


Figure 4. Variation of True Heat Input as a function of clock position, Weld #1 fill pass 2, Trail Torch, Contractor B

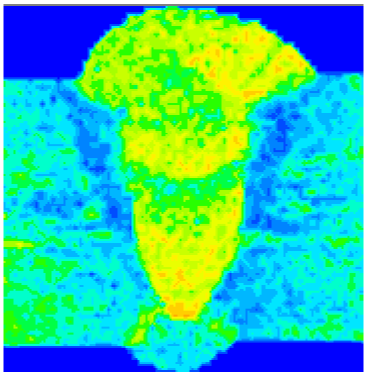
3.3 Tensile and Hardness Results

The tensile properties were measured with a strip tensile specimen [2, 4]. Results obtained from welds made at contractor A are shown in Figure 5(a) and Figure 6(a) and those made at contractor B are shown in Figure 7(a) and Figure 8(a). Detailed results are summarized in Table 7.

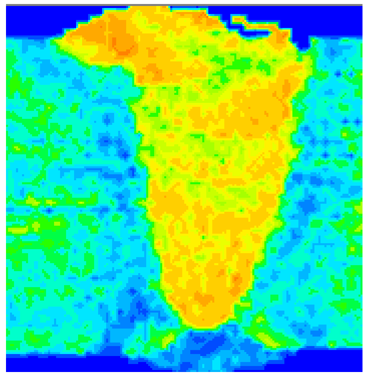
Results from weld 952-G, shown in Figure 5(a), made by contractor A reveal that the tensile results are quite similar among the different clock positions. The stress strain curve at clock position 3 is the highest followed by that at clock positions 6 and 12. The stress strain curves follow the trend in the microhardness maps shown in Figure 5(b) through Figure 5(d), which indicate the largest amount of as-deposited (high hardness) region at clock position 3 followed by 6 and 12 . Results from weld 952-H, shown in Figure 6(a), indicate that the stress strain curve at clock positions 12 and 3 are very close, whereas the curve at clock position 6 is the highest. The corresponding microhardness maps, shown in Figure 6(b) through Figure 6(d) indicate that clock positions12 and 3 are very similar, whereas clock position 6 has the highest amount of as-deposited regions (high hardness) indicative of higher strengths compared to that at the 12 and 3 clock positions. This is because of the decreased penetration and lack of optimum cap pass alignment at clock position 6, which decreases the remelting and reheating of the underlying passes leaving more as-deposited region in the weld.

Results from weld 1 and 2, shown in Figure 7(a) and Figure 8(a), made by contractor B reveals that the tensile results at clock position 6 is slightly higher than that at clock positions 12 and 3, which are very close to each other. The stress strain behavior from these welds, in general, follow the corresponding microhardness graphs shown in Figure 7(b) through Figure 7(d), and Figure 8(b) through Figure 8(d) respectively.

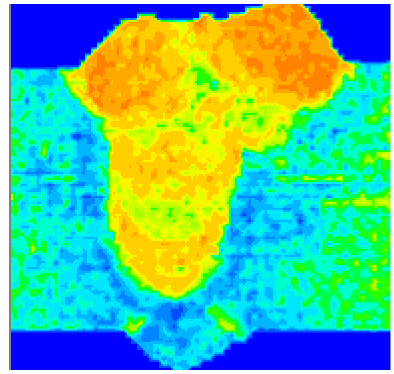
With welds from both contractors, in all cases, the weld metal stress strain curves overmatch the longitudinal pipe stress strain curves and in most cases the hoop stress strain curves. This indicates the weld composition provided by PT2 is in a regime where its strength remains high regardless of the differences in pass sequence and cooling behavior at the different clock positions around the pipe in these 5G narrow gap dual torch welds with different torch spacings.



b) 12 o'clock

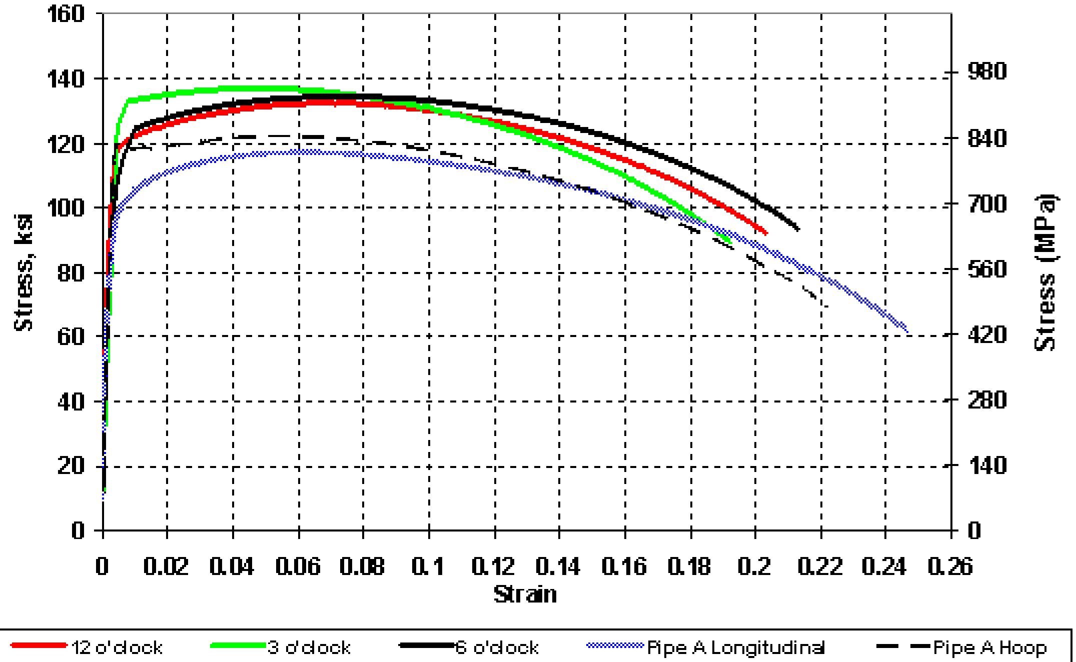


c) 3 o'clock



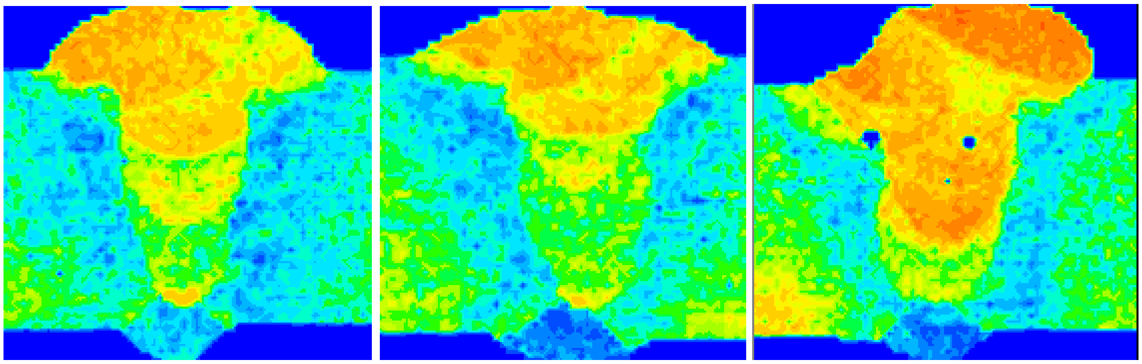
d) 6 o'clock

300g Vickers Scale

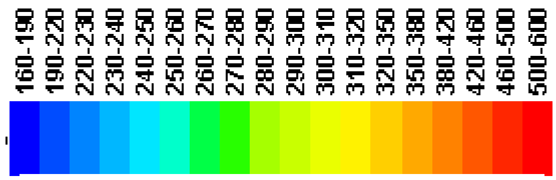


a) AWM strip tensile

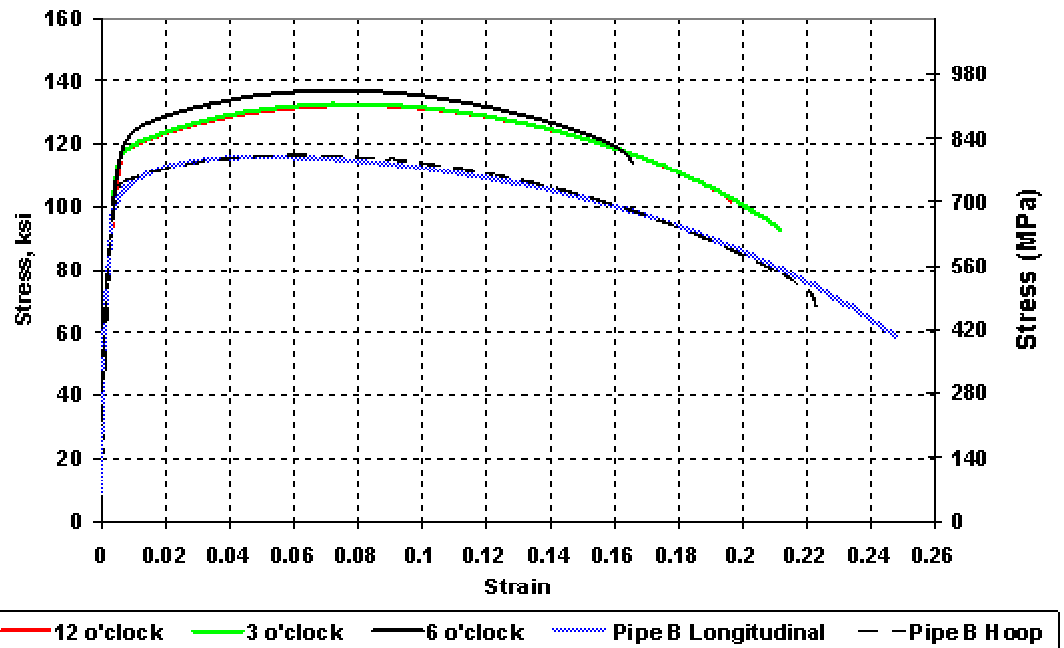
Figure 5. 952-G Stress-Strain Curves and Microhardness Maps (dual torch, PT2)



b) 12 o'clock c) 3 o'clock d) 6 o'clock



300g Vickers Scale



a) AWM strip tensile

Figure 6. 952-H Stress-Strain Curves and Microhardness Maps (dual torch, PT2)

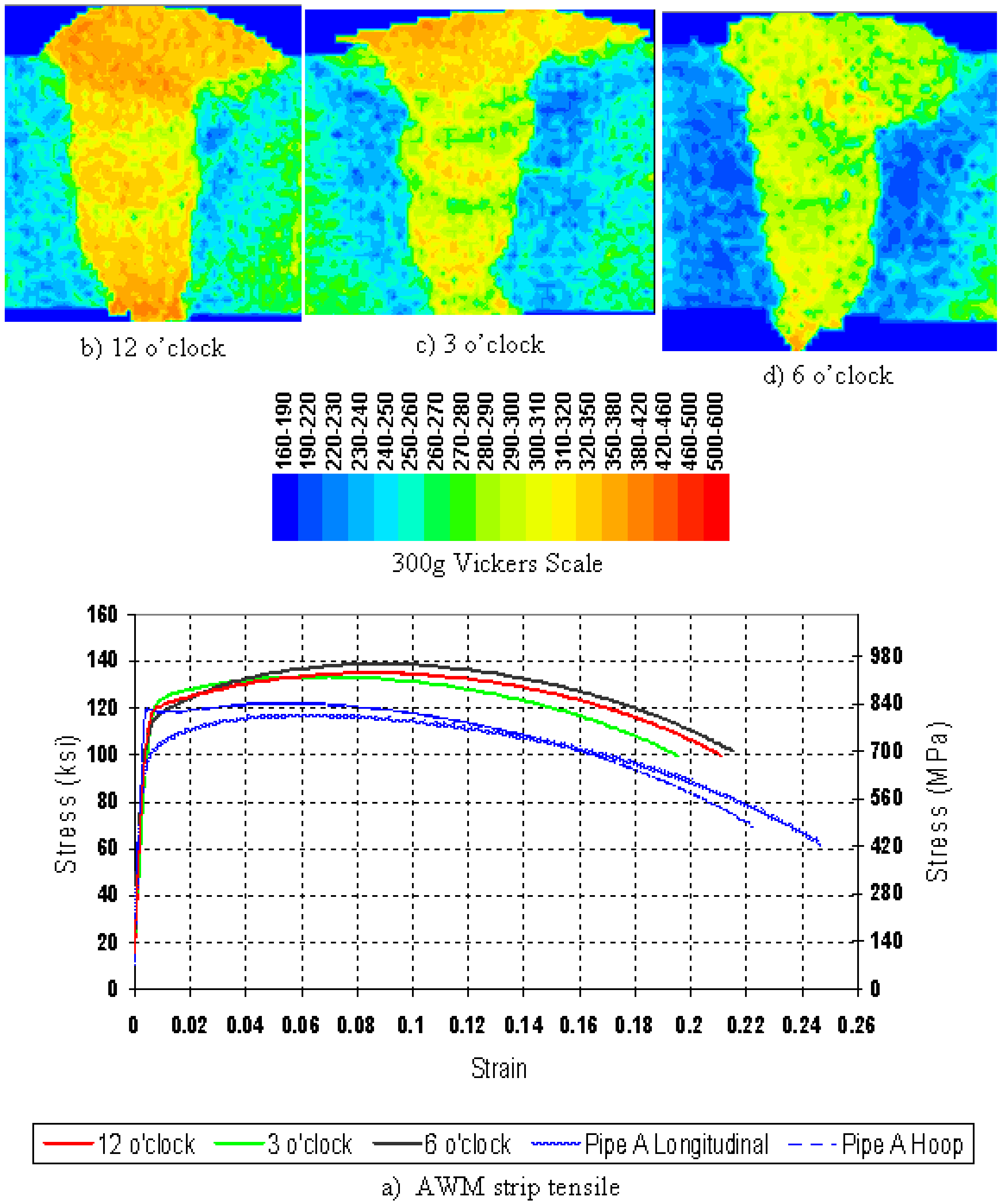
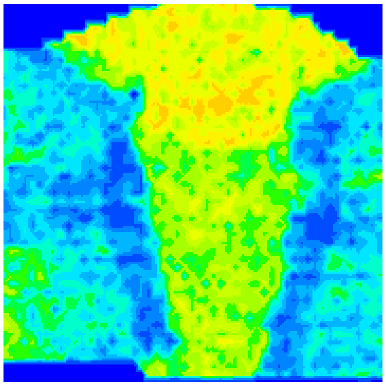
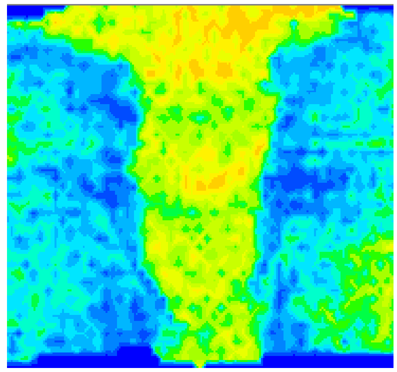


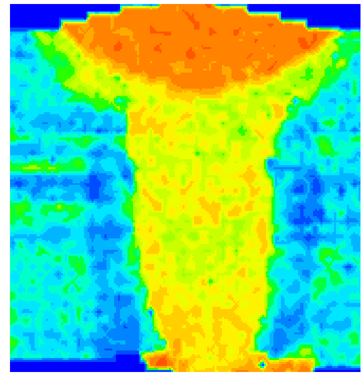
Figure 7. Weld 1 Stress-Strain Curves and Microhardness Maps (dual torch, PT2)



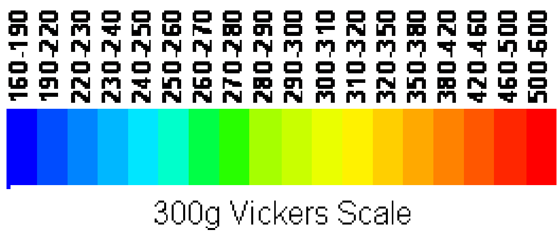
b) 12 o'clock

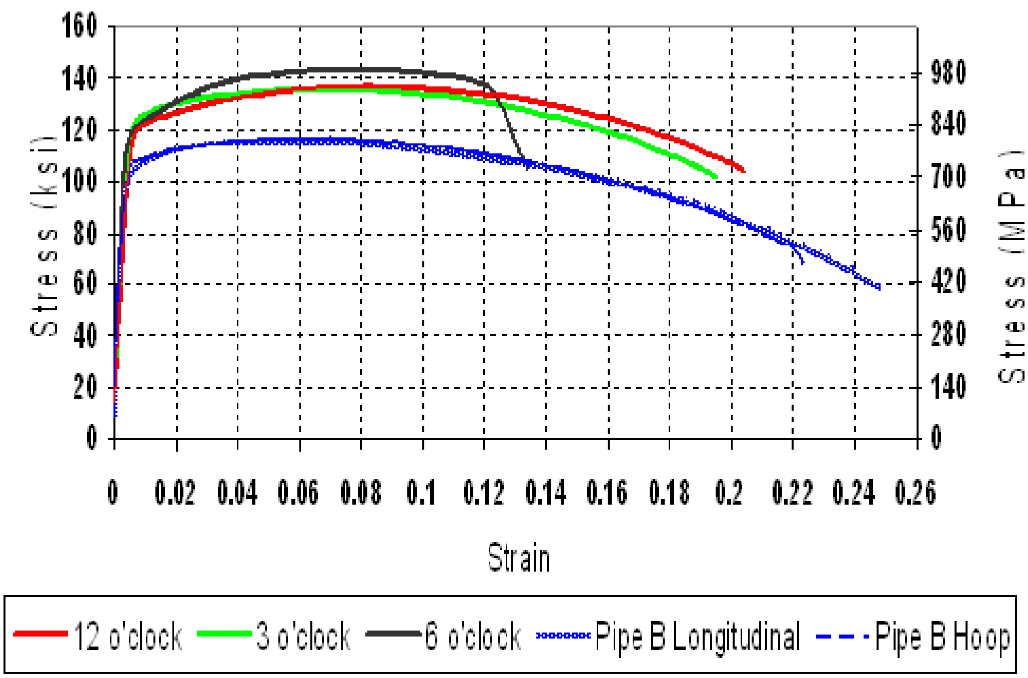


c) 3 o'clock



d) 6 o'clock





a) AWM strip tensile

Figure 8. Weld 2 Stress-Strain Curves and Microhardness Maps (dual torch, PT2)

Comparison of the tensile results between the welds made by contractor A vs. those made by contractor B reveals some interesting results. As shown earlier in Table 2, contractor A used dual torches with a 121 mm (4.75 in.) spacing, pulse waveform and 85%Ar/15%CO_2 gas, preheat and interpass temperatures between 100^0C to 125^0C and True Heat Inputs in the range of 0.6-0.8 kJ/mm (15-19 kJ/in) as they went around the pipe. Contractor B used dual torches with 51 mm (2 in.) spacing, globular arc transfer, 50%Ar/50%CO_2 gas, higher interpass temperatures between 120^0C to 155^0C, but True Heat Inputs in the range of 0.45-0.56 kJ/mm (11-14 kJ/in) as they went around the pipe. The lower True Heat Inputs in the latter case compensated for the preheat and interpass temperatures being biased in the direction of lower strengths for welds 1 and 2. Therefore, their tensile strengths are very similar to that of welds made by Contractor A.

These results are summarized in Figure 9 and Figure 10 where the 0.2% yield strength, flow stress at 1% total strain and tensile strengths are plotted against the true heat inputs with clock positions delineated in them. Just as in the case of the single torch welds reported earlier [2], there is some scatter associated with the reported 0.2% offset yield strength in the dual welds made by both contractors. As explained earlier, this could be an artifact of the process of testing the strip tensile specimens for the following reasons. The thinner gage cross section area of 4.8 mm x 7.9 mm (0.19 in. x 0.31 in.) combined with asymmetrical geometry of the strip tensile specimen compared to a round specimen, can render the test vulnerable to some variation in its early part in the linear elastic range. Since the 0.2% yield strength calculation is based on the slope of the linear elastic portion of the stress strain curve, any testing related variation in this elastic portion can cause this slope to differ significantly from the elastic modulus. This can result in variations in the reported yield strength from similar stress strain curves. However, the flow stress measured at 1% total strain from the stress strain curve is very consistent and mirrors the variation in tensile strength quite well. At 1% total strain, the stress strain curve is out of the linear range, and in the steady state plastic portion, and the resulting flow stress is not vulnerable to testing related variation in the elastic range. As a result, for strip tensile specimens $\leq$ 5 mm thick ($\leq$ 0.2 in.) and possibly also circular tensile specimens of $\leq$ 5 mm diameter ($\leq$ 0.2 in) small cross sections, the 1% flow stress may be a more consistent indicator of yield behavior in X100 welds until the testing methodology is refined enough to eliminate the variations in the elastic range.

In the range of heat inputs utilized in these welds, no general trends are evident between the strengths and the heat inputs. The tensile strengths obtained with welds made by contractor A in the 3 and 6 clock positions are slightly higher than that in the 12 clock position. The high strength at clock position 6 is by virtue of the decreased penetration even at the higher heat input. The highest strengths obtained with welds made by contractor B are also in the 6 clock positions for the reasons mentioned before. These results indicate that in addition to the variables already identified, in 5G welds, there is an additional variable of clock position which can affect the mechanical properties of the weld. However, the differences in tensile strengths as a function of clock position are much smaller in these dual torch compared to the single torch cases [2]. This could be due to the weld composition and microstructure from wire PT2 in these dual torch welds being relatively insensitive to the cooling rates encountered in the narrow heat input range employed at the different clock positions. However, just as in the case of the single torch welds, better control of heat input should provide less scatter in mechanical properties at the different clock positions around the weld.

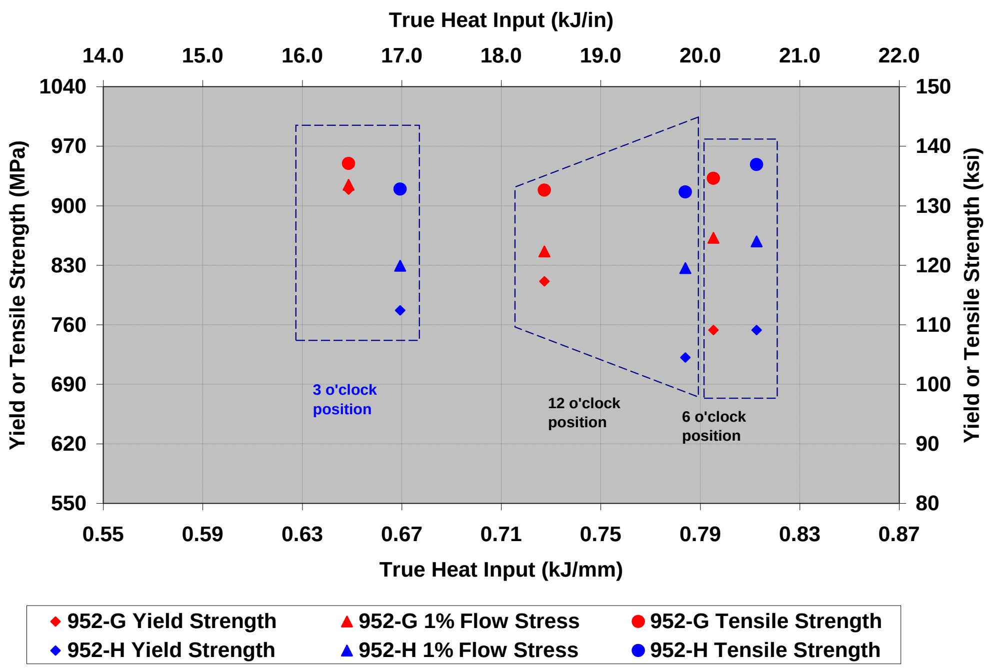


Figure 9. 0.2% Offset Yield, Flow Stress and Tensile Strengths vs. True Heat input – Contractor A Dual Torch

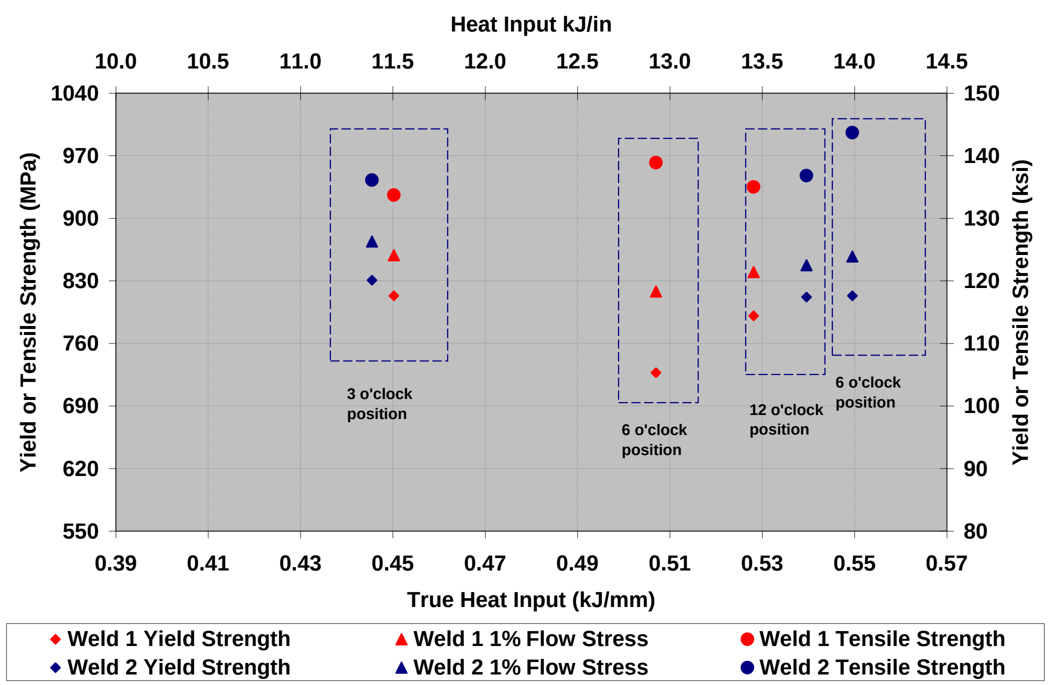


Figure 10. 0.2% Offset Yield, Flow Stress and Tensile Strengths vs. True Heat input – Contractor B Dual Torch

Softening is observed in the HAZ in all clock positions, especially at clock position 12. Hardness values as low as 210 VHN were observed in the HAZ, and most of the hardness values are in the 220-250 VHN range. In contrast, the weld metal hardness is in the range of 290-350

VHN. When the hardnesses are compared to the single torch welds, the increased softening with the dual torch becomes evident with the dual torch at 50.8 mm (2 in.) torch spacing, but less so with the 121 mm (4.75 in.) torch spacing. The HAZ with 50.8 mm (2 in.) dual torch spacing seems to extend out to about 5 mm, whereas with the 121 mm (4.75 in.) spacing, it seems to be 2-2.5 mm. These trends are reflected in the transverse hardness traverses shown in Figure 11 and Figure 12.

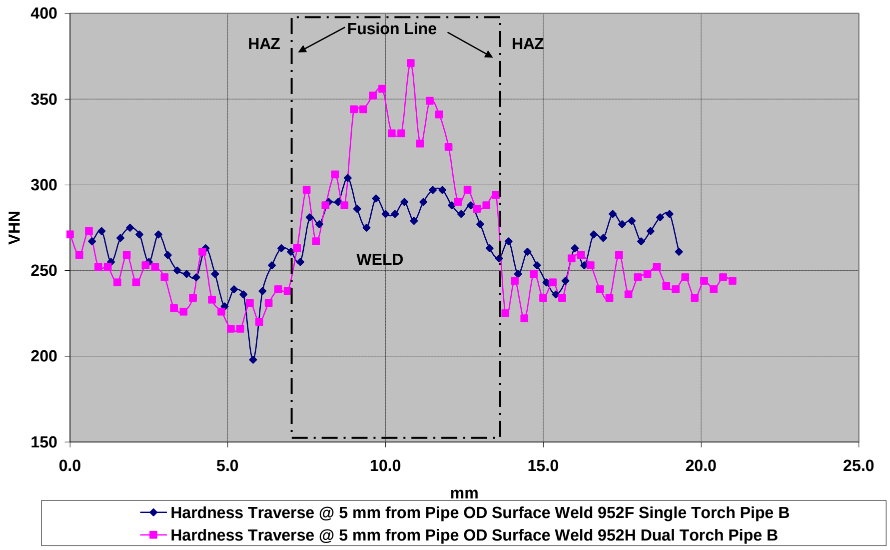


Figure 11. Transverse Microhardness Traverse of Single Torch Welds 952-F and Dual Torch Weld 952-H @ 12 o'clock position made by Contractor A on Pipe B.

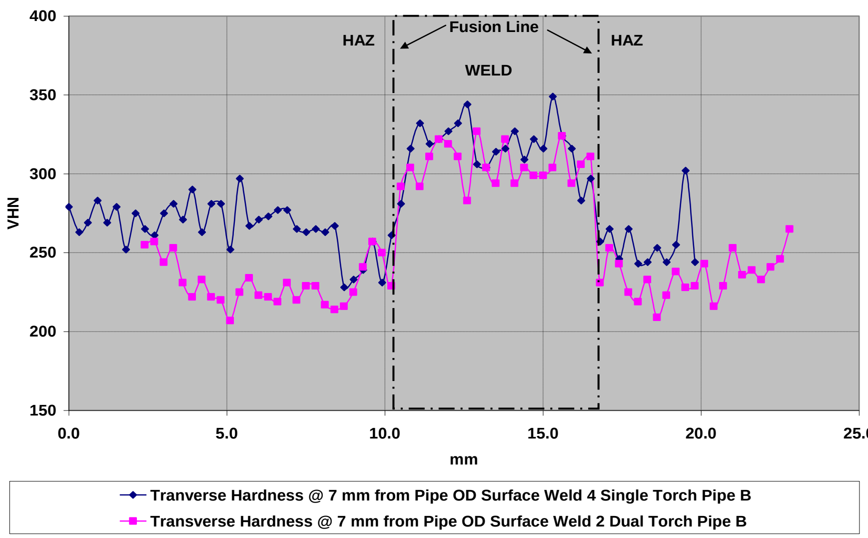


Figure 12. Transverse Microhardness Traverse of Single Torch Weld 4 and Dual Torch Weld 2 @ 6 o'clock position made by Contractor B on Pipe B.

3.4 Charpy Impact Strength Results

Charpy toughness from welds made by contractor A was in the range of 159-234J at -20^{0}C from pipe A and 175-224J at -20^{0}C from pipe B, as shown in Figure 13. In weld 952-G, it seems that the average weld metal charpy toughness increases in going from the 3 and 12 to the 6 clock position. Coincidentally, this also corresponds with an increase in heat input, but as was observed before with single torch welds [2], the effect of clock position confounds the analysis between charpy toughness and True Heat Input. In addition, weld 952-H doesn't show any trend of toughness with True Heat input. As a result, in the range of heat input observed in these welds, no definite correlations between True Heat Input and toughness can be discerned. In general, the 6 clock position provides the highest weld metal toughness compared to the other positions similar to the trend observed with the single torch welds [2]. Interestingly, the 6 clock position also provides high strength in the weld metal by virtue of a high amount of as-deposited structure as seen in Figure 5(d) and Figure 6(d). This implies that the increase in weld metal Charpy toughness at clock position 6 is not due to a general softening, but presumably due to a higher toughness as-deposited microstructure obtained with the PT2 consumable. The corresponding HAZ Charpy toughness values were in the range of 244-250J from pipe A and 164-300J from pipe B.

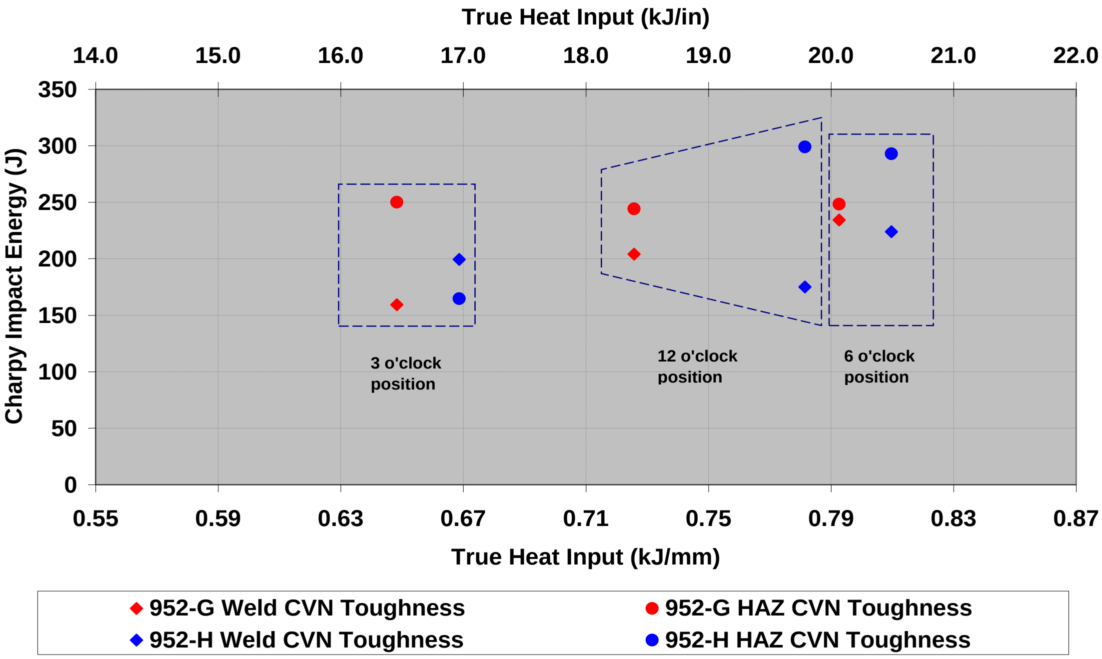


Figure 13. Charpy V-notch impact toughness at -20^{0}C as a function of Pipe and Clock Position, Contractor A, Dual Torch Welds

Welds made by contractor B provided corresponding toughness values in the range of 99 -161J from pipe A and 88-106J from pipe B as shown in Figure 14. The corresponding HAZ charpy toughness values were in the range of 195-289J from the first weld and 127-254J from the second weld. In this case, with weld 1 and weld 2, no consistent trends between toughness and clock position or True Heat Input can be discerned. Also, the weld metal toughness values are much lower than that obtained from contractor A. This is because of the higher CO_2 in the shielding gas mixture resulting in higher oxygen levels in the weld metal. These results indicate that 50%Ar/50%CO_2 gas mixtures may be detrimental for weld metal toughness in these high strength welds. The lower HAZ toughness with weld 2 compared to that in weld 952-H, especially in the 12 clock position, is presumably because of higher hardness in the weld 2 HAZ due to banding effects in the pipe as seen in Figure 8(b).

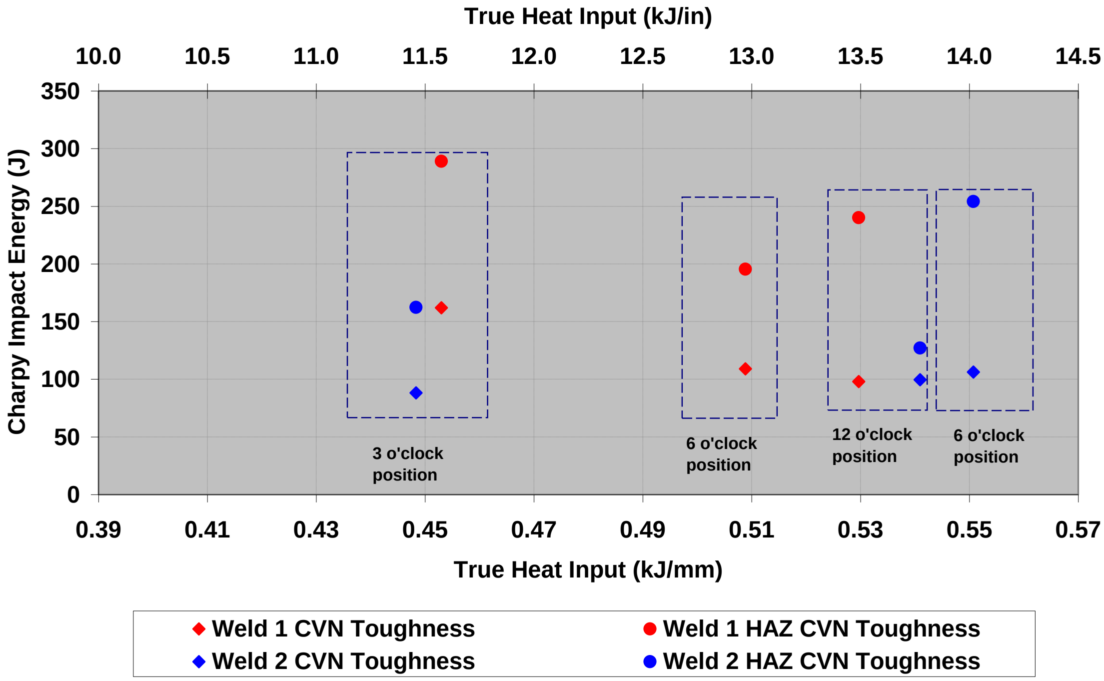


Figure 14. Charpy v-notch impact toughness at -20^{0}C as a function of Pipe and Clock Position, Contractor B, Dual Torch Welds

In general, in dual torch welds 952-G and 952-H, the weld metal and HAZ charpy toughness values and the HAZ toughness values from welds 1 and 2 obtained were quite high, barring some occasional low values in the HAZ. The lower weld metal charpy toughness values from welds 1 and 2 made by contractor B is because of the higher %CO_2 in the shielding gas mixture resulting in higher oxygen levels in the weld metal. No significant differences in HAZ charpy toughness with heat input were observed in welds made by either contractor. No significant trends between HAZ toughness and True Heat Input were seen with Pipe A or with Pipe B.

It seems that in a couple of these welds (952-G and 952-H), just as in the single torch welds [2], the clock position has an affect on the charpy toughness, whereby clock position 6 provides higher toughness, followed by clock positions 12 and 3 in welds. The effect of True Heat input on toughness is not clear because of the interaction effect with clock position which complicates the analysis. Details of all mechanical property results and chemical compositions are summarized in Table 7 and Table 8 respectively.

3.5 Considerations for Other Welding Processes

3.5.1 Double Jointing

Double jointing of high strength pipe is a process that involves joining two smaller lengths of pipe, typically 12 m (40 ft.), in the pipe mill or on a pipe lay barge, by girth welding to form a longer length of pipe of about 24 m (80 ft.) maximum. The finished length of pipe is usually limited by the carrying capacity of transportation systems and lifting capacity of cranes on site. The advantage of double jointing lies in being able to reduce the number of main line girth welds which results in significant savings due to reduced welding time in the field and increased productivity. This joining process is usually done with submerged arc welding (SAW), but other processes such as dual torch GMAW are being considered. Double joint girth welds are subjected to similar inspection criteria as the mainline girth welds and have to provide consistent mechanical properties around the pipe. Additionally, for strain based designs they have to overmatch the pipe tensile properties and provide weld metal toughness that matches the values obtained with the main line girth welds.

In double joint welding with SAW, the grooves are much wider than that employed in main line girth welding, and the heat inputs used are much higher because of higher productivity enabled by minimizing the number of passes. Consequently, the weld metal composition and properties are influenced more by the amount of dilution of the weld metal from the base pipe. The extent of this influence varies depending on the pipe compositions and consumable compositions employed. Furthermore, the extent of this dilution is determined by the welding practice (e.g. number of passes, bead placement, current type and polarity, etc.). The resulting heat input becomes one of the primary variables that determine weld and HAZ properties. Often, SAW is done with AC/DC machines with varying polarity, in which case specifying the True Heat Input becomes a larger challenge than when using a single current type/polarity. These features can make ensuring consistent mechanical properties with double jointing of X100 pipe a daunting task.

Measurement of True Power or True Energy [2] can also be applied to double jointing to get accurate measures of True Heat Input. This is very important because the True Heat Input is a major factor in determining the extent of base metal dilution in the weld which in turn determines the weld metal properties. Also, True Heat Input is a major factor in determining the HAZ properties, particularly with SAW where the heat inputs are potentially much higher that for GMAW. Measurement of True Heat Input provides a very accurate measure of this variable by rendering it independent of the machine and waveform used in the process. Experiments, such as those used here for GMAW [2], can then be performed with the double jointing process to establish statistical models between the essential welding variables and the weld mechanical properties. However, the models can be expected to be more complex because at the higher heat inputs commonly employed in double jointing, the weld composition will vary with both consumable selection and amount of dilution and likely will have a significant impact on the weld mechanical properties. As a result, significant interaction between the essential welding variables such as True Heat Input, preheat and interpass temperature, consumable composition, pipe composition and groove geometry can be expected in their effect on the weld and HAZ mechanical properties. The linear correlations between the welding variables and weld mechanical properties that were observed with the narrow groove GMAW welds cannot be expected to hold true, and significant non linearity leading to more complex models could be expected with double jointing. However, simplification of the problem by holding certain variables such as pipe composition, consumable composition, and groove geometry reasonably constant, the other welding variables such as True Heat Input and preheat and interpass temperatures can be correlated to the weld and HAZ mechanical properties. This approach can be effective, but only after determining that there is not an important interaction that would be lost by holding a variable constant. Such correlations could be developed for controlled cases of pipe/consumable combinations, which can be the focus of future work. This approach can provide a basis for extending the control methodology to double jointing. The principles embodied in the modeling and subsequent control methodology employed in the narrow groove girth welds would also hold true with regard to minimizing the variation in mechanical properties around double jointed welds on X100 pipe.

3.5.2 Flux Cored Arc Welding

Flux cored arc welding (FCAW) is commonly used in line pipe construction, particularly with lower strength pipe grades. Gas shielded flux cored arc welding (FCAW-G) has been used for tie-in or repair welding of pipe in some X100 demonstration projects [1]. To date, GMAW has been preferred for main line welding with FCAW-G reserved for tie-in or repair. Self shielded flux cored arc welding (FCAW-S) consumables with the ability to satisfy the mechanical properties requirements for X100 pipeline applications are yet to be developed.

Both of these FCAW processes employ tubular wires with fill ingredients that produce slag during welding. FCAW-G resembles GMAW except for the fact that the slag-metal reactions can be significant in determining effective heat inputs and cooling rates. FCAW-S does not utilize shielding gas, and its fill ingredients are even more influential in determining the heat input and mechanical properties of the weld. The fill ingredients contain active ingredients that undergo oxidation or react with each other resulting in a very complex heat balance during the welding process. Furthermore, the heat balance associated with these fill ingredients will also be affected by the heat input employed during welding. Consequently, measurements of True Heat Input will not provide the full picture of the total heat input into the process. As a result, modeling the correlation between essential welding variables and mechanical properties is expected to be very complex. Just as in the case with double jointing, simplifying the problem by reducing the number of variables operating simultaneously could make the modeling effort plausible. This could be the focus of future work, particularly with FCAW-G, a process for which consumables close to satisfying mechanical properties requirements are becoming available. If workable models are obtained that correlate weld mechanical properties with a simplified set of welding variables, control methodology for consistent mechanical properties could be developed for FCAW of X100 pipe.

3.5.3 Shielded Metal Arc Welding (SMAW)

In high strength pipelines, SMAW almost exclusively is used for tie-in, repair. It is used for mainline welding with lower strength pipe grades. SMAW is a manual process and welding is done in the constant current mode. Because of the manual nature of this process, the heat input is not monitored as stringently as for the automatic welding processes. Control of heat input is often dependent on the dexterity and skill level of the welder. Current is usually monitored and recorded by visual observations of the current meter on the welding machine, and the travel speed is determined by the welder. While this process does not lend itself easily to control in the conventional sense as obtained with the GMAW process, some measures can be taken to reduce the variation in heat input. If True Power can be recorded in the machine continuously, then efforts can be made to reduce variation in the power input into the weld. If the travel speed can be kept within reasonable control, efforts to minimize heat input variation around the pipe can be implemented. As with the fill material in FCAW wire electrodes, the coating of the SMAW electrodes can have active ingredients that influence the heat input into the weld, and to that extent, True Power monitoring will not capture these effects. But within a constant set of conditions of consumable composition, pipe composition and groove geometry, True Power monitoring could still provide means to reduce variation in the welding process.

4 CONCLUSIONS

The essential welding variables and control methodology identified for single torch X100 welding can be extended successfully to dual torch X100 welding. In addition to the primary variables such as consumable composition, True Heat Input and preheat and interpass temperature, the importance of torch spacing in dual torch welding has been demonstrated. Smaller torch gaps can have a significant softening effect on weld properties in both the weld metal and HAZ.

The correlations between these primary welding variables and weld mechanical properties can be described very well with linear models. The associated transfer functions have enabled the determination of control limits for the welding variables, for a given weld metal composition, to obtain the weld mechanical properties such as yield and tensile strengths within desired ranges for different torch gaps. This has enabled the development of a control methodology for the essential welding variables for dual torch welding.

Implementation of the control methodology for the essential welding variables in dual torch field welding practice is feasible, provided the True Heat Input during welding is monitored and controlled within the prescribed limits with appropriate instrumentation, and the preheat and interpass temperature is controlled within the prescribed limits. However, similar to the observations for 5G single torch welds, clock position seems to influence both the strength and the toughness measurements, which goes beyond what can be explained by True Heat Input variation alone. This effect of clock position can provide more variation in the mechanical properties of the weld, albeit the observed differences were smaller than with single torch welds [2]. However, following the proposed control methodology to reduce the variation in True Heat Input as a function of clock position will help in reducing the overall variation in mechanical properties.

Extension of this methodology to other processes such as double jointing with SAW, FCAW and SMAW is possible. However, the analysis can be complicated by significant interactions involving slag-metal reactions and alternative current types/polarities. Nevertheless, system simplification to reduce the number of variables operating simultaneously could conceivably render these processes more amenable to the modeling and control methodology formulated in this work.

Table 7. Mechanical Properties of Dual Torch Pipe Welds made during Shop Welding to mimic Field Welding Conditions

Weld ID	Pipe	Clock Position	Mean True Heat Input HI_{TE} for All Fill Passes kJ/mm	Std Dev of HI_{TE} for All Fill Passes	0.2% Yield Stress (MPa)	Flow Stress @ 1% Total Strain (MPa)	UTS (MPa)	Weld Metal CVN @ -20°C (J)			Average (J)	SD	HAZ CVN @ -20°C (J)			Average (J)	SD
Welds made by Contractor A																	
952-G	**A**	12	**0.73**	**0.07**	809	843	914	232	207	172	**204**	**30**	247	229	256	**244**	**14**
952-G	**A**	3	**0.65**	**0.07**	915	920	945	182	163	133	**159**	**25**	245	249	256	**250**	**5**
952-G	**A**	6	**0.79**	**0.03**	752	859	928	228	260	214	**234**	**24**	247	249	248	**248**	**1**
952-H	**B**	12	**0.78**	**0.01***	720	824	912	165	175	184	**175**	**9**	281	308	312	**300**	**17**
952-H	**B**	3	**0.67**	**0.09**	775	827	916	203	195	199	**199**	**4**	99	148	247	**164**	**75**
952-H	**B**	6	**0.81**	**0.04**	752	855	944	220	271	180	**224**	**46**	279	301	300	**293**	**12**
Welds made by Contractor B																	
Weld 1	**A**	12	**0.53**	**0.05**	789	837	931	91	100	104	**99**	**7**	138	293	289	**240**	**88**
Weld 1	**A**	3	**0.45**	**0.02**	811	856	922	113	156	216	**161**	**52**	286	291	289	**289**	**3**
Weld 1	**A**	6	**0.51**	**0.04**	726	816	958	113	100	114	**109**	**7**	226	235	125	**195**	**61**
Weld 2	**B**	12	**0.54**	**0.02**	809	845	943	99	102	98	**99**	**2**	58	165	159	**127**	**60**
Weld 2	**B**	3	**0.45**	**0.02**	828	871	938	77	83	104	**88**	**14**	174	104	209	**162**	**53**
Weld 2	**B**	6	**0.55**	**0.03**	811	854	991	103	111	104	**106**	**4**	233	258	271	**254**	**19**

*Incomplete Data

Table 8. Chemical Composition of Dual Torch Welds made during Shop Welding to mimic Field Welding Conditions

Weld ID	Pipe	Clock Position	%C	%Mn	%Si	%Ti	%Cr	%Mo	%Ni	%N	%O	%S	%P	%Cu	%Nb	CE IIW	Pcm	Cen	Bs	Ms
Welds made by Contractor A																				
952-G	A	12	0.091	1.67	0.57	0.034	0.22	0.45	1.49	0.004	0.037	0.008	0.012	0.19	0.009	0.62	0.27	0.42	547	424
952-G	A	3	0.092	1.57	0.53	0.035	0.21	0.46	1.50	0.004	0.032	0.009	0.015	0.19	0.005	0.60	0.27	0.41	555	427
952-G	A	6	0.097	1.63	0.61	0.041	0.24	0.48	1.62	0.005	0.030	0.007	0.013	0.18	0.004	0.63	0.28	0.44	541	420
952-H	B	12	0.093	1.69	0.55	0.027	0.36	0.42	1.59	0.004	0.027	0.009	0.010	0.25	0.006	0.65	0.28	0.44	534	419
952-H	B	3	0.092	1.70	0.58	0.024	0.41	0.44	1.77	0.004	0.032	0.009	0.009	0.27	0.008	0.68	0.29	0.46	521	415
952-H	B	6	0.105	1.69	0.65	0.034	0.35	0.48	1.78	0.004	0.027	0.010	0.010	0.22	0.004	0.69	0.30	0.50	519	409
Welds made by Contractor B																				
Weld 1	A	12	0.092	1.60	0.63	0.024	0.39	0.50	1.99	0.007	0.045	0.010	0.009	0.217	0.005	0.685	0.291	0.458	519	414
Weld 1	A	3	0.095	1.58	0.60	0.022	0.41	0.48	1.88	0.005	0.048	0.010	0.008	0.236	0.007	0.678	0.292	0.463	524	415
Weld 1	A	6	0.095	1.63	0.61	0.025	0.40	0.47	1.88	0.004	0.032	0.010	0.009	0.243	0.007	0.683	0.293	0.466	521	414
Weld 2	B	12	0.093	1.62	0.64	0.026	0.30	0.51	1.91	0.004	0.040	0.010	0.010	0.188	0.009	0.666	0.287	0.450	525	415
Weld 2	B	3	0.088	1.62	0.66	0.027	0.32	0.51	1.98	0.004	0.047	0.011	0.009	0.180	0.008	0.669	0.284	0.440	522	416
Weld 2	B	6	0.097	1.61	0.69	0.029	0.31	0.52	1.96	0.004	0.032	0.010	0.009	0.269	0.008	0.681	0.298	0.471	522	412

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